National Aeronautics and Space Administration

FY23 Strategic Initiatives Research and Technology Development (SRTD)

Miniature Space Optical Clock

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Strategic Focus Area: Space Clocks | **Strategic Initiative Leader:** Todd Ely

OBJECTIVES

The overall objective of the initiative effort is to develop and demonstrate the miniature optical clock concept that will have a short-term stability of 1E-14 $\tau^{-1/2}$ and long-term stability of 1E-16, 10x better than the state-of-the-art microwave clocks such as Deep Space Atomic Clock (DSAC). With the single trapped ion as the atomic reference approach, it is possible to make the whole clock system small enough to deploy in Deep Space.

BACKGROUND

Currently, JPL's DSAC is the state-of-the-art microwave clock of its size. To reach beyond the DSAC capability, one will have to take the new approach of the *optical clock* where the clock ticking rate is at hundreds of THz rather than tens of GHz. The high oscillation frequency enables the clock stability and accuracy performance beyond today's microwave clocks. This effort aims at developing key components to advance the state-of-the-art Space Clock - ultimately leading to a complete optical space clock system. The targeted mSOC clock performance (stability and accuracy) and SWAP-C (size, weight, power, and cost) have been chosen to maximize the utility of this instrument for future JPL/NASA missions.

APPROACH AND RESULTS

The fundamental structure of an atomic clock is straightforward – an atomic reference is used to steer and stabilize an oscillator that does the clock ticking. The clock performance critically depends on the atomic reference. This approach leverages JPL's unique capability of ion trapping in a small sealed vacuum package to develop an atomic reference of a single trapped ytterbium ion. Previously, we fabricated the trap tube and established the necessary experimental clock tabletop subsystems to characterize and validate the atomic reference performances. We also demonstrated the ability to trap and confine a single ytterbium ion in the tube with a long ion lifetime. This year, we successfully constructed a next-generation trap tube with compensation electrodes, established experimental capabilities for the optical clock operation, and observed an indication of the clock transition. This demonstration paves the way for the miniature space optical clock application.

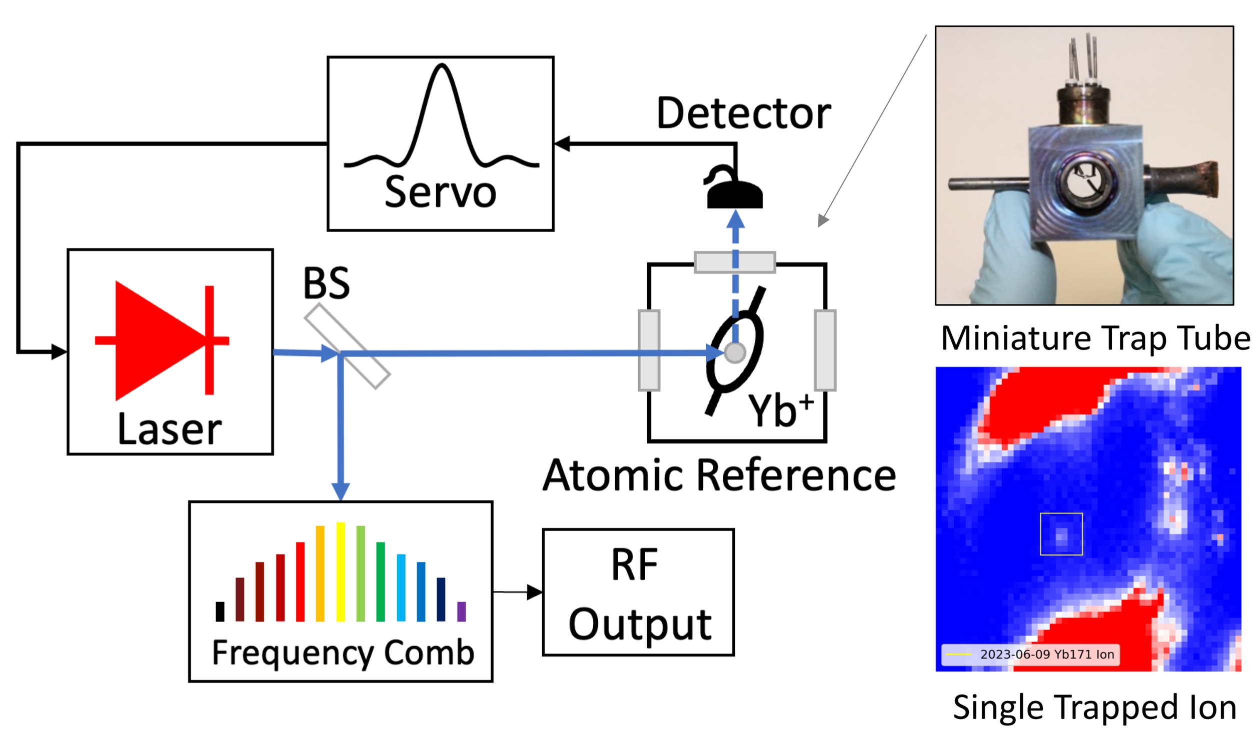

Figure 1. Miniature space optical clock concept

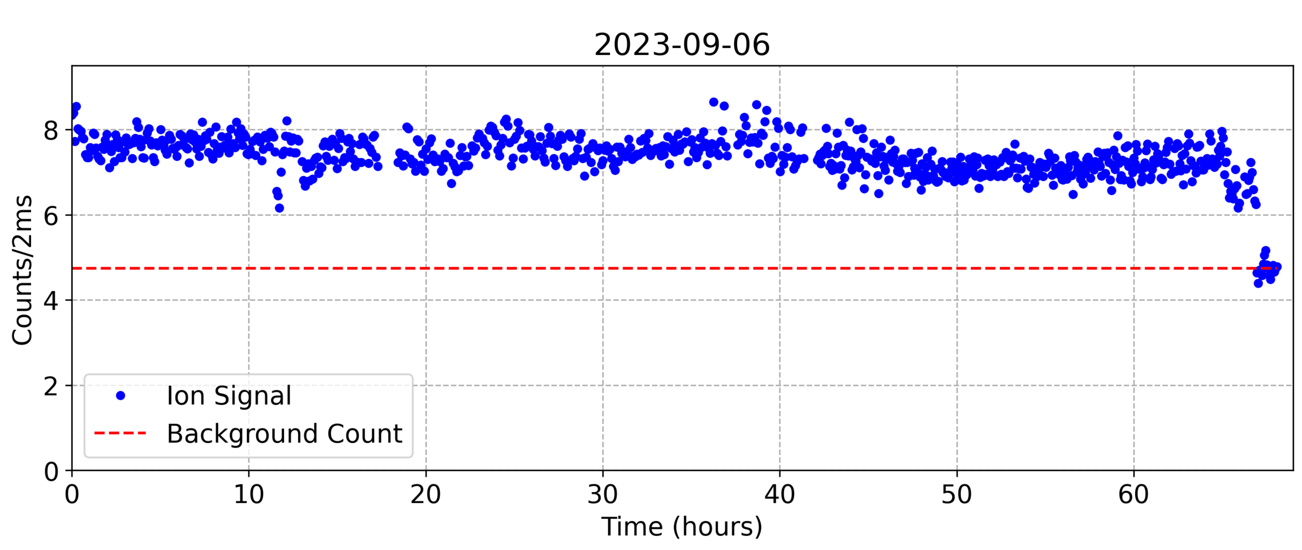

Figure 2. An ion lifetime of over 60 hours after 2 years of operation.

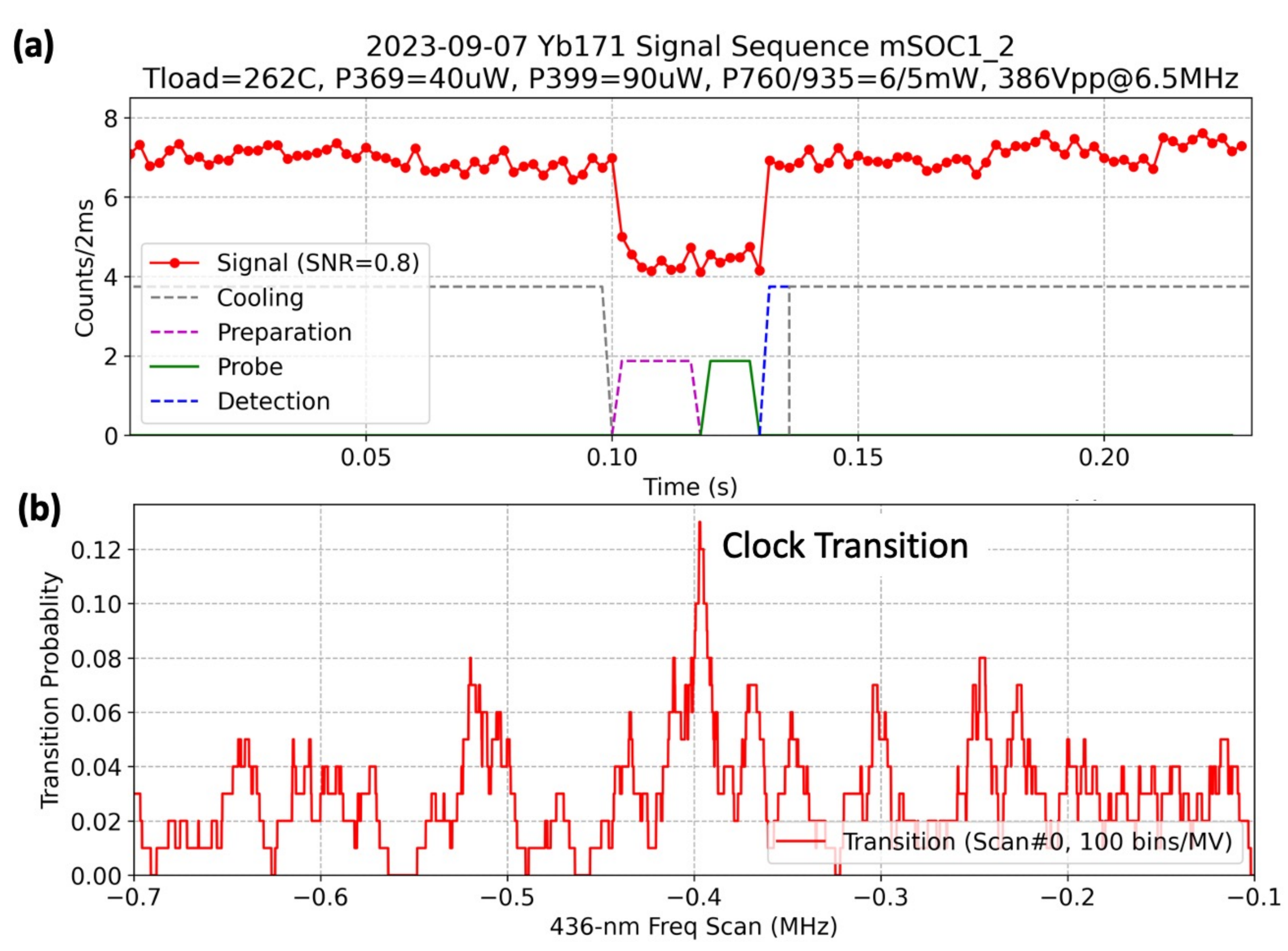

Figure 3. (**a**) Timing sequence. The ion is cooled for 50-100 ms, followed by 20 ms of state preparation, 10 ms of clock interrogation, and 4-10 ms of detection. (**b**) Clock transition. Using the frequency comb and high finesse wavemeter, we can lock the clock laser frequency to the compact reference cavity within 1 MHz from the atomic clock transition. We observed an indication of clock transition by a moving average of 100 data points after 4-15 hours of frequency scanning.

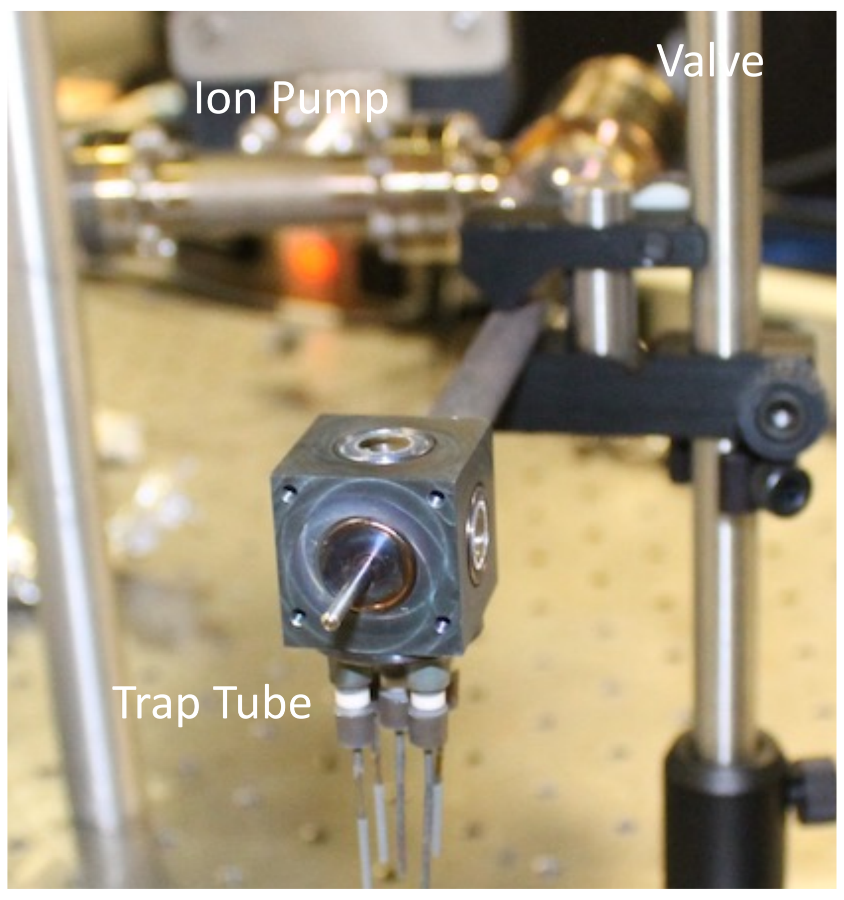

Figure 4. A photograph of the next generation trap tube with compensation electrodes. The new trap tube can compensate for any stray electric fields and minimizes the ion micromotion.

SIGNIFICANCE/BENEFITS TO JPL AND NASA

The new capability of the miniature space optical clock will make a significant impact on NASA's Deep Space Network antenna resource utilization efficiencies, system autonomy and robustness, and space Position, Navigation, and Timing capabilities in general. It could enable new scientific measurements as well as detections of dark matter ultra-light fields and improve radio tracking planetary gravity and atmosphere occultation measurements.

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Publications:

[A] W. Zhang, T. Le, T. Hoang, M. Langlois, N. Yu, and A. Matsko, "Compact Fabry-Perot cavity for Yb ion clock," submitted to Conference Photonics West, LA203, Laser Resonators, Microresonators, and Beam Control XXV, 2023.

[B] Nan Yu, Thai M. Hoang, Mehdi Langlois, Thanh Le, Andrey B. Matsko, Sean Mulholland, Yuna Park, John Prestage, and Wei Zhang, "Progress in the miniature trapped ion optical clock development with 16 cc sealed trap tube," 9th Symposium on Frequency Standards and Metrology, Kingcliff, NSW, Australia. Oct. 16-20, 2023.

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